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TOPEX/Poseidon Operational Orbit Determination Results Using Global Positioning Satellites

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Results of operational orbit determination, performed as part of the TOPEX/Poseidon ('1'/1') Global Positioning Satellite (GPS) demonstration experiment, are presented in this paper. Elements of this experiment include the GPS satellite constellation, GPS Demonstration Receiver on-board '] '/1], six ground GPS receivers, the GPS Data Handling Facility and the GPS Data Processing Facility (GDPF). Carrier phase and P-code pseudo range measurements from up to 25 GPS satellites to the seven GPS receivers are processed simultaneousl y with the GDPF software MIRAGE to produce orbit solutions of T/P and the GPS satellites. Daily solutions yield sub-decimeter radial accuracies compared to other GPS, LASER and DORIS precision orbit solutions.

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The Global Positioning Satellite (GPS) Data Processing Facility (GDPF) was developed to demonstrate operational orbit determination and navigation support for TOPEX/Poseidon. Orbit solutions are based on data collect ed by the GPS Demonstrat ion Receiver (GPSDR), on-board TOPEX/Poseidon, and six ground stations. In addition, the GDPF is intended to evolve into a NASA resource for future low Earth orbiting missions under the. Office of Space Communications.

An updated software set, based on the J]'], institutional Orbit Determination Program (ODP), was created and named "MIRAGE." It stands for: Multiple Interferometric Ranging Analysis using GPS Ensemble. MIRAGE maintains the complete interplanetary capabilit y of the 011P software wit h the additional multi-satellite ant] preci sion mode lling

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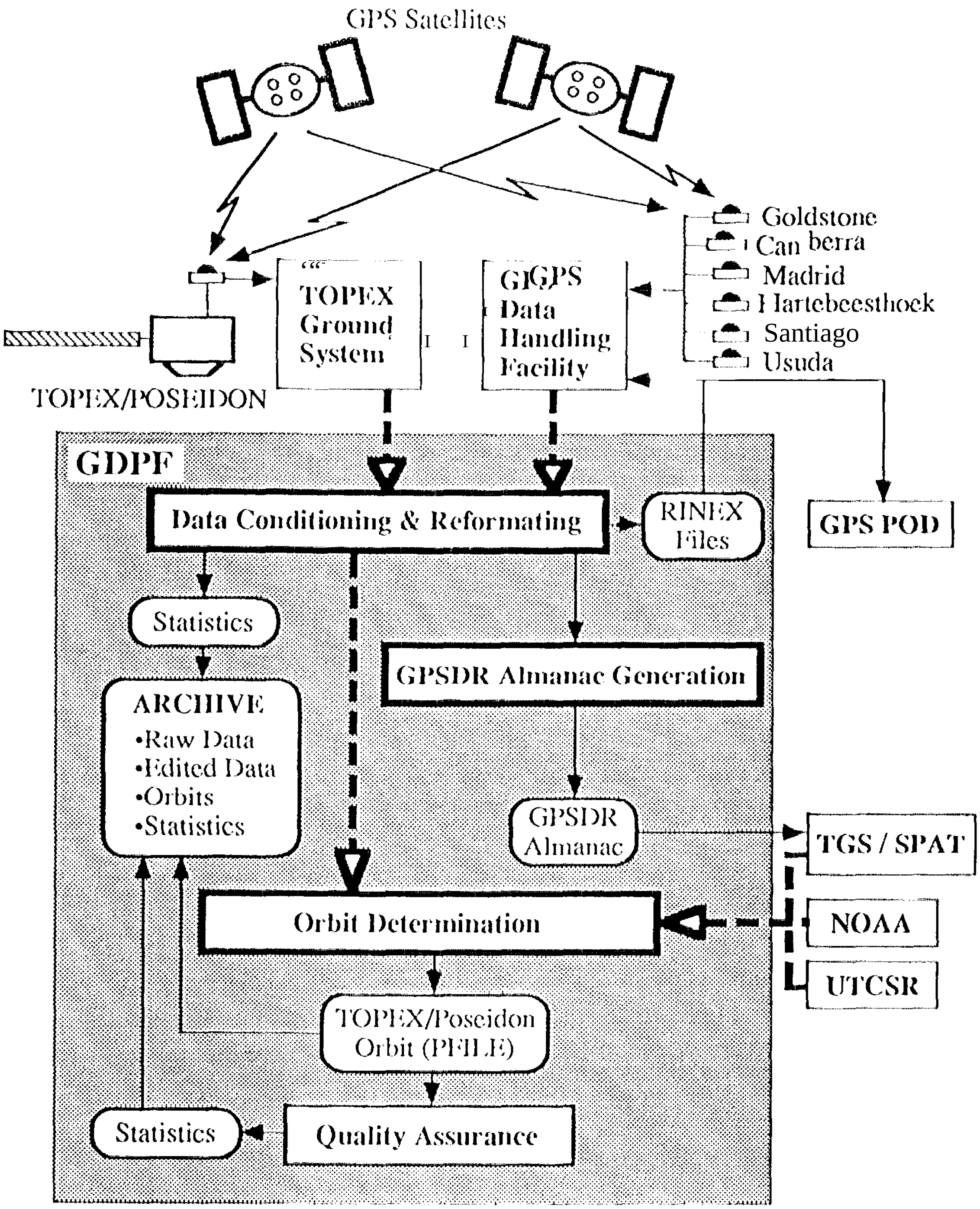
Figure 1 - . GPS. Data Processing Facility Interfaces



features required for sub-decimeter orbit determination. The scope of the GDPF includes: preprocessing observations, Performing orbit determination, producing predicted GPS and TOPEX/Poseidon satellite almanacs for mission operations, and archiving raw and processed data. Figure 1. shows the interfaces of the GDPF.

OBSERVATION PRE-PROCESSING

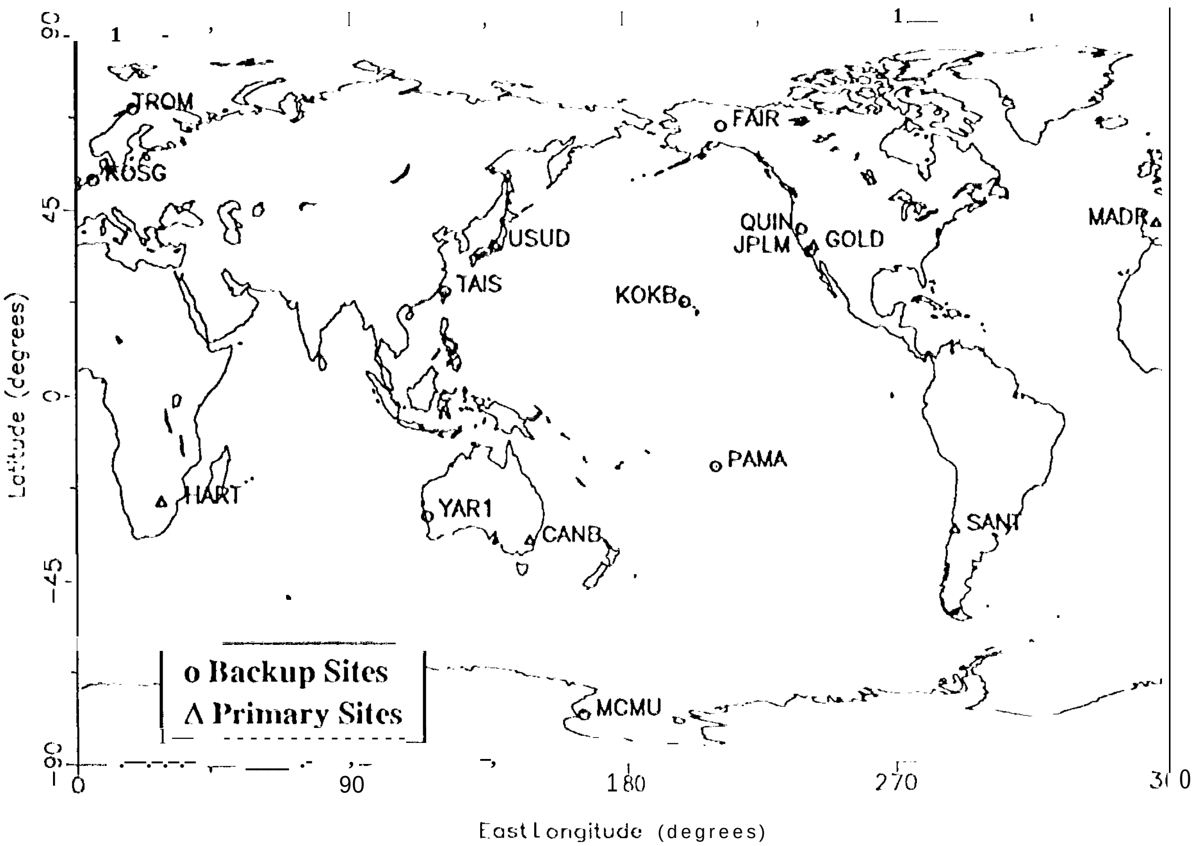
Daily TOPEX flight receiver raw data are collected from the TOPEX Ground System within 24 hours of the last observation. The raw data consists of carrier phase every second and P-Code pseudorange every 10 seconds. in addition, the GPSDR on-board navigation solution (i.e., clock, position and velocity) are provided every 10 seconds.

Automated reformatting and outlier and cycle slip editing is performed first. Next, the. data are decimated to five. minute intervals and a time tag correction, based on a linear fit to the navigation clock solution, is applied. Finally, linear combinations of the pseudorange (P_1 and P_2) and carrier phase (L_1 and L_2) dual frequency measurements are computed to produce ionosphere calibrations. These are applied to the raw P_1 and L_1 observations to produce the or-bit determination observables P_C and L_C.

The ground GPS receiver observations are available from the GPS Data Handling Facility about 36 hours after the last data were collected. Both the carrier phase and psuedorange are, provided in RINEX[1] format at 30 second samples. The same editing and calibration steps are performed as described above for the GPSDR. In addition to the six core ground sites, data from nine backup sites are also collected and processed. The primary and backup ground station locations are shown in Figure 2.

For MIRAGE orbit determination processing, a merged file of edited GPSDR and ground receiver data is created in standard MIRAGE format. Two additional text files, in RINEX format, are produced for export. One is the raw GPSDR data while the other is the edited, calibrated and compressed GPSDR measurements. All files are archived along with data collection and pre-processing statistics.

Figure 2. - TOPEX/GPS Ground Station Network



ORBIT DETERMINATION STRATEGY

Thirty hour data sets are constructed from the pre-processed observations to produce a 24 hour orbit solution. The additional data is fit to allow for internal consistency checks of the daily overlaps. Global GPS constellation coverage is realized by selecting a minimum of six ground station GPS receiver sites. Additional sites are selected to fill gaps during primary site outages.

Orbit determination using MIRAGE consists of three major steps. Iteration through each step is performed until convergence of the state solutions and observation residuals is achieved. The three steps are:

- Trajectory Propagation
- Observation Processing
- Filtering and Smoothing

Trajectory Propagation - To achieve sub-decimeter accuracies several dynamic force models arc required, Tables 1 and 2. summarize the force models used in the. numerical integration of the TOPEX/Poseidon and GPS satellite trajectories. Reference frame, force, and measurement model parameters are based on '1'01'1 iX/Poseidon and International Earth Rotation Service (IERS) standards[2-3].

Table 1. - Force Models for TOPEX/Poseidon

Model:	**Description:**
N-Body:	All Planets, Sun, Moon
Earth Geopotential:	50x50 truncated JGM-2
Indirect Earth-Moon Oblateness:	2x2 Lunar Model
Solid Eath Tides:	IERS
Ocean Tides:	JGM-2
Rotational Deformation:	IERS
Relativity:	Point Mass limb + Lense-Thirring
Solar Radiation Pressure:	Conical Shadow Model
Atmospheric Drag:	DTM Model
Albedo anti Infrared Earth Radiation:	2nd Degree Zonal Model
Empirical Accelerations:	Once/Rcv and Twice/Rev Models

Table 2. - Dynamic Force Models for GPS Satellites

Model:	**Description:**
N-Body:	All Planets, Sun, Moon
Earth Geopotential:	12x12 truncated JGM-2
Indirect Earth-Moon Oblateness:	2x2 Lunar Model
Solid Eath Tides:	IERS
Ocean Tides:	JGM-2
Rotational Deformation:	IERS
Relativity:	Point Mass Earth + Lense-Thirring
Solar Radiation Pressure:	Rock4 and Rock42 Models

Observation Processing - Both carrier phase and P-Code pseudo-range arc processed, Table 3. lists the measurement models used for producing observation residuals. Again, these models arc adopted based largely on IERS standards.

Table 3 - Measurement Models

Model:	Description:
Solid Earth Tides:	0th, 1 st and 2nd order Corrections
Rotational Deformation (Pole Tide):	IERS
Ocean Loading:	IERS
Polar Motion:	UTCSR‡
Plate Motion:	Linear Velocities[4]
Earth Center of Mass Offset:	Currently Zero

Filtering and Smoothing - The filter and smoother generate corrections to the parameters affecting the trajectory propagation and the observat ion processing. MIRAGE employs a numerically stable square root information filter which has the capability to compute. the smoothed est imates oft ime varying stochastic parameters. Our orbit determination strategy employed a fiducial concept whine three ground receivers which were assumed to have well known coordinates are held fixed while the filter estimates the positions of three non-fiducial ground stations in addition to the states of the GPS satellites and TOPEX/Poseidon. The filtering strategy consisted of a two stage process -- dynamic tracking followed by reduced dynamic tracking. In dynamic trecking the accuracy oft he orbit is limited by the precision of the dynamic models applied during trajectory propagation, In reduced dynamic tracking, the high quality geometric information provided by the GPS measurement system is utilized to obtain a high precision "1'OP]{X/Poseidon trajectory. Essentially, reduced dynamic tracking exploits the extreme precision of carrier phase tracking by using it to smooth the geometric solutions obtained from the less precise pseudo-range measurements. Although the success of the reduced dynamic technique is contingent on high precision modeling of the GPS observations, the accuracy of the resultant trajectories are not degraded by deficiencies in the a priori dynamical models.

Data Weighting - The measurement precision expected from the GPSDR and ground station observations was determined from ground test prior to launch. Data weights consistent with these analyses are applied during filtering arc shown in Table 4.

Table 4.- GPS Observation Weights

Data Type	GPSDR	Ground Station
Carrier Phase	2 cm	1 cm
Pseudo-Range	2 m	1 m

‡ Daily rapid sevice soutions from University of Texas

Stochastic Clock Estimation - To eliminate synchronization errors due to unstable oscillators, clock biases at the receivers and GPS transmitters arc estimated at each measurement time, In the filter, one ground clock is chosen as a reference and a stochastic clock bias is estimated at each of the other receivers and GPS transmitters. A white noise stochastic process is employed with a batch length coinciding with the measurement intervals and the estimated smoothed clock biases are fed back to the observation processing module. As with standard double differencing techniques, the stochastic clock estimation strategy eliminates common clock errors but the stochastic method avoids both the difficulties of selecting a set of non-redundant double difference combinations and the data noise correlations inherent in differenced measurements.

Stochastic Phase Bias Estimation - Continuously tracked GPS carrier phase precisely measures the relative range change between a GPS transmitter and its receiver. However, the carrier phase is ambiguous which necessitates the estimation of a constant phase bias for each continuous pass between a transmitter ant] a receiver. in the filter, each phase bias is estimated as a white noise stochastic parameter which remains constant over a pass. At tracking discontinuities, the filter applies a white noise stochastic update for the bias parameter corresponding to an individual tm~smitter/receiver pair. The smoother generates a time profile of phase bias corrections which are applied during subsequent observation processing. This stochastic phase bias estimation strategy is efficient in terms of computation time and memory requirements but it dots not attempt to resolve the integer nature of the phase biases.

Stochastic Estimation of Tropospheric Fluctuations - The model for troposphere delay is decomposed into a wet and dry component.

$$\rho = \rho_{z_d} R_d(\theta) + \rho_{z_w} R_w(\theta)$$

where ρ_z is the zenith delay and R is a mapping function which maps the zenith delay to the line of site at elevation O. The fluctuations in the wet zenith delay were modeled as a stochastic random walk. The wet zenith delay was estimate.d at 5 mi nutc intervals (coincident with the measurement interval) using an a priori sigma of 5 cm and an effective batch-to-batch sigma of 3 mm for the noise driving the random walk process. As with the phase and clock biases, the smoothed time profile of the stochastic fluctuations were fed back into the observation processing module. on subsequent iterations of the orbit determination program.

Reduced Dynamic 'l"racking - 'l'he MIRAGE filter execute.s the reduced dynamic tracking strategy by modeling the three-dil~~cl~sior~al accelerations on TOPEX/Poseidon as exponentially time correlated stochastic processes. 'l'he relative weighting of the dynamics and geometry may be adjusted by varying the time constant and the magnitude of the. process noise uncertainty. A large time constant corresponds to a dynamic strategy while a short time constant emphasizes the geometry. in the orbit determinant ion for TOPEX/Poseidon the three accelerations were updated at five minute intervals; the time constant was 15 minutes with a corr esponding batch-to-batch sigma of 7×10^{-9} m/s^2 for the radial acceleration and 14×10^{-9} m/s^2 for the spacecraft X and Y accelerations. "l'his choice of filter parameters allowed deficiencies in the non-gravitational force models to be compensated by the stochastic accelerations; however, enough d ynamical information is retained so that temporary degradat ion of the viewing geomet ry would not seriousl y reduce the accuracy of the output trajectory[5-7].

Table 5. - Estimated Parameters

Parameter(s)	Number of Parameters
TOPEX State	6
GPS States (20 Satellites Average)	120
Station Locations (3 Stations)	9
GPS Solar Pressure Scale. Factors and Y-Bias	6(I
Empirical Dynamic	9
Stochastics: (30 hour arcs with 5 minute updates)	
Troposphere	6
TOPEX and Ground Clocks (1 master clock fixed)	26
Carrier Phase Biases	**-130**
Accelerations (X,Y,Z)	3
TOTAL	~369

01{111'1" DETERMINATION ACCURACY

Before launch, the Ml RAG]; software was inter-compared with the GEODYN and UTOPIA software. sets from the Goddard Space. Flight Center (GSFC) and the University of Texas Center for Space Research (UTCSR) respectively. 'l'he inter-comparison validated all dynamic trajectory models for TOPEX/Poseidon and verified the laser range measurement models. For all cases, including the combined models case, the maximum radial differences were about one centimeter or less for a 10-day orbit.

An additional inter-comparison with the UTCSR GPS software MSODP to validate trajectory models for the GPS satellites was performed. All but the occulting solar radiation pressure produced sub-centimeter, 10-day orbit comparisons. The solar radiation pressure inter-comparison tests have been postponed due to the expected release of improved models.

After launch, the operational orbit determination accuracies have steadily improved as the procedures and techniques have been fine tuned. Accuracy comparisons are. broken into three distinct processing phases. The dates and groundtrack repeat cycles for each are:

PHASE	DATES	CYCLES
I	November 3, 1992 - December 21, 1992	5-9
2	December 22, 1992 - May 2, 1993	10-23
3	May 3, 1993 - July 16, 1993	24-30

Data prior to cycle five were not considered for this analysis due. to difficulties in the early days of the GPSDR plus the occurrence of several anti-spoofing days. Phase 1 processing was performed before many of the internal and external consistency checks (see below) were used; thus, is not representative of the achievable accuracies. Phase 2 processing used 24 hour arcs with the 'dynamic' technique augmented with empirical once and twice per revolution parameters. Phase 3 consists of 30 hour arcs with the additional 'reduced dynamic' tracking strategy.

Statistics collected for the GPS carrier phase residuals (observations minus compute.d values) are presented in Figure 3. These residuals are from Phase 2 and 3 only. A marked reduction in the residuals is seen when the 'reduced dynamic' technique is employed. All gaps are due to GPS constellation anti-spoofing activity when no GPSDR data were available.

TOPEX/Poseidon orbit comparisons have displayed sub-decimeter agree.ments in the radial component with one day GPS Precision Orbit Determination (POD) solutions and orbits derived from Laser and DORIS data, Figures 4 and 5. show the three dimensional and radial RMS orbit differences during phases **2** and 3. The MIRAGE 'dynamic' solutions are compared with another 'dynamic' solution determined from laser data. The laser solution is an approximately 10 day fit from GSFC's GEODYN program. The basis for the comparisons in Figure 5 are the MIRAGE 'reduced dynamic' solutions. They are compared with another reduced dynamic solution from the GPS GIPSY-OASIS software. that is part of the GPS Demonstration Experiment POD segment.

Figure 3. - MIRAGE Observation Residuals

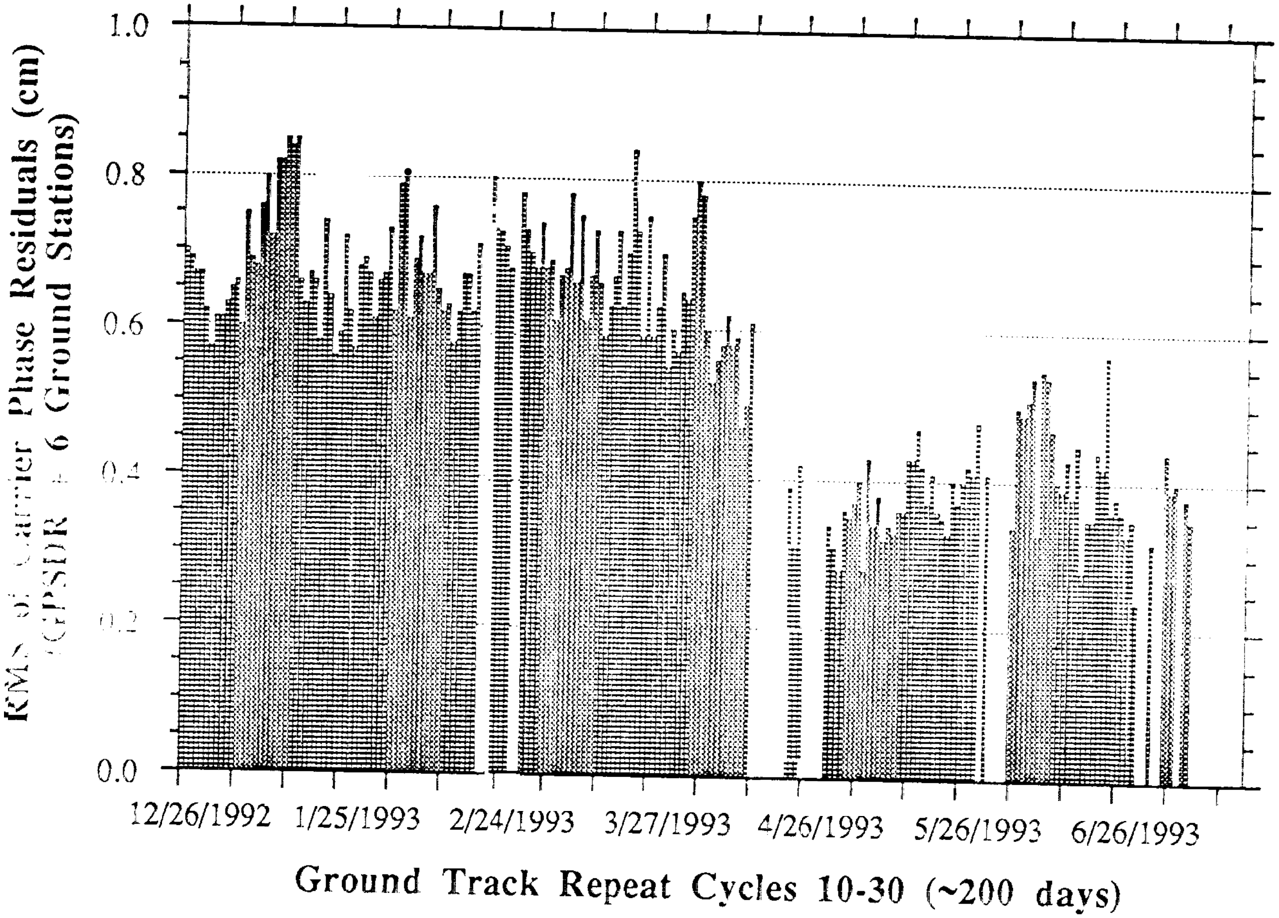


Figure 4. - MIRAGE GPS Dynamic Orbit Comparisons

GPS vs LASER (NASA POE)

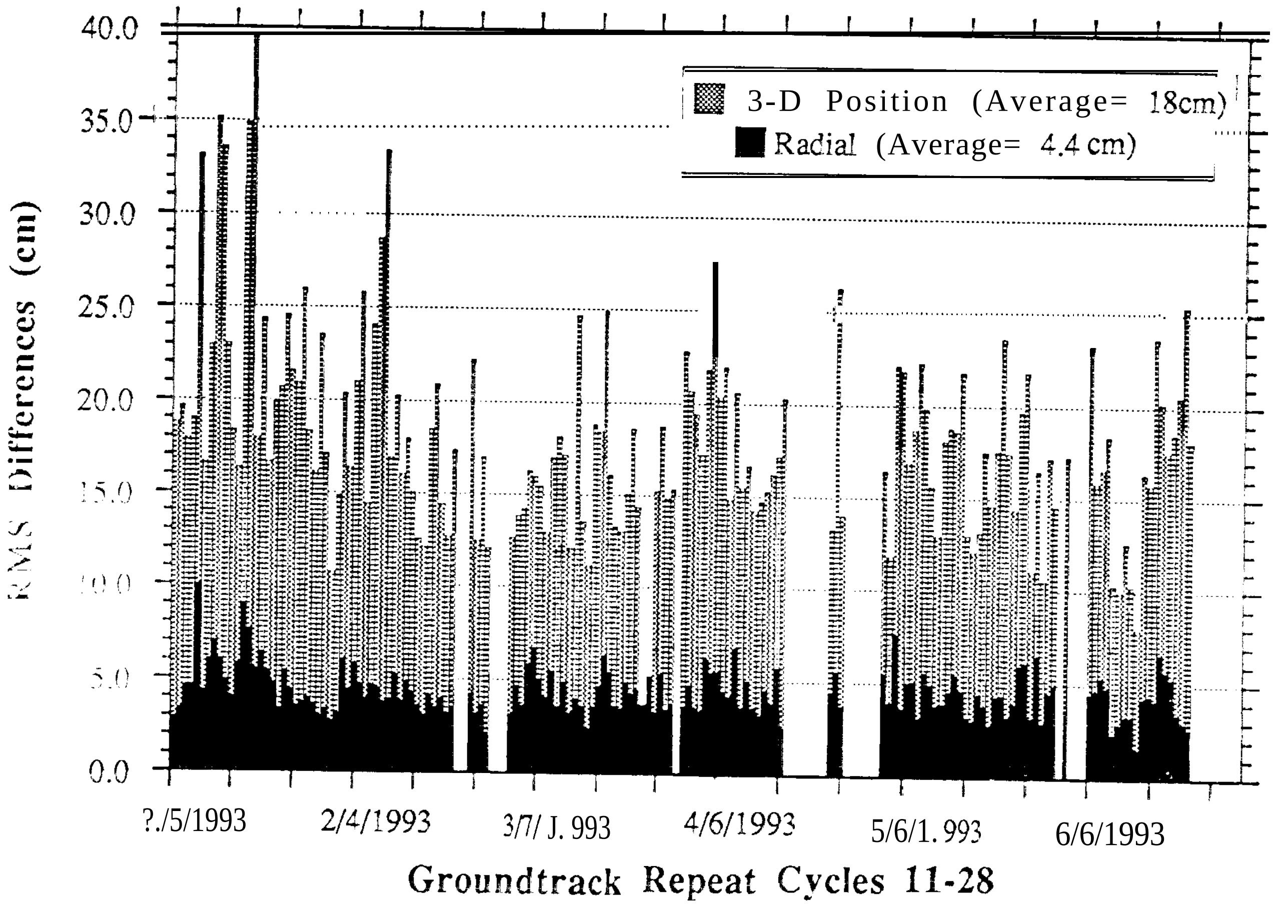
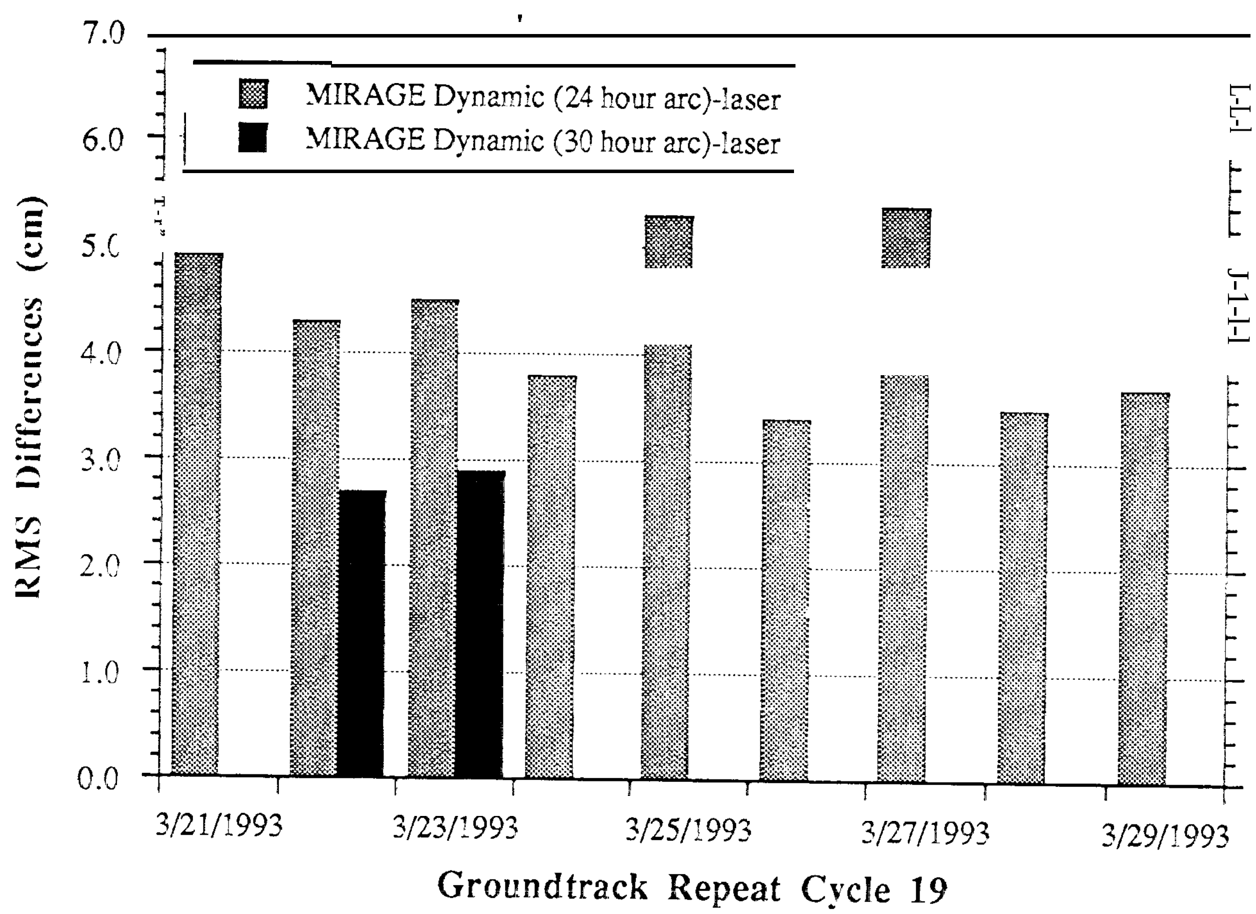


Figure 5. - MIRAGE GPS Reduced Dynamic Orbit Comparisons



P RECESSING AUTOMATION ANI) ERROR CHECKING

One goal of the GDPF was to automate as much of the processing as possible. Beginning with the data collection through the delivery of final products, each aspect of the processing was examined and automated by means of standard Unix scripts and X-Window interfaces to the scripts. Dashed lines in Figure 1. demote automatic procedures that do not require human intervention. User inputs changing from day to day such as the date, duration, and transmitting ant] receiving participants arc controlled via a graphical X-windows interface which eliminates user input errors and ensures operational consistency. 1 Error mail message.s are generated to alert operators of malfunctions in the automated non-interactive scripts.

OFF-NOMINAL TOPEX/POSEII)ON ATTITUDE MODELLING

Robust processing of off-nominal TOPEX/Poseidon satellite attitude events is available in two ways. First, the actual attitude e.vent change times (e.g., fixed to sinusoidal yaw steering event) are designed as user inputs. Secondly, the trajectory processing can use the attitude quaternions from telemetry. So far, all attitude events, except orbit maintenance mane, euvers, have been accurately modelled with the user input overrides. The actual telemetr y was on] y required fort he maneuver.

LASER ANI) DORIS I) ATA TYPES

In addition to the GPS P-code pseudo-range and carrier phase observables, the MIRAGE software can process Satellite Laser Range (S1 .R) and Doppler Orbitography and Radiopositioning Integrated by Satellite (I) OR IS) data. S1 .R and DORIS data types were incorporated to support TOPEX/Poseidon verification activities. The S1 .R orbits arc used routinely for the Interim Geophysical Data Records (IGDR) science product[8]. Orbit file formats are identical for all data types (i.e., PFILE format); therefore, no interface changes are required for IGDR processing with MIRAGE GPS orbits. A utility has also been developed as part of the MIRAGE software to convert any MI RAGE orbit file into the Precision Orbit Ephemeris (POE) format.

TOPEX/POSEI DON MISSION OPERATIONS SUPPORT

A routine GDPF task is to produce GPSDR almanac predictions for initial acquisition operations. Almanac data are produced twice weekly as a contingency for rapid GPSDR failure recovery. The dat a are delivered to the Spacecraft Performance Anal ysis Team for reformatting and subsequent uplink to the GPSDR by the Flight Control Team.

GPS ANTI-SPOOFING RESULTS

During GPS constellation anti-spoofing activities only CA-code pseudo-range and L1 carrier phase are available from the GPSDR. however, an internal receiver calibration provides for an ionosphere correction to the ground receiver data. Sub-decimeter radial differences have been achieved for limited sets of data by producing an approximate ionosphere calibration. "Ibis calibration is derived by subtracting the CA-code carrier phase from the pseudo-range and smoothing the resulting signal to remove multipath. This yields an ionosphere correction that can then be applied to both the CA-rode pscude-range and carrier phase.

GDPF RESOURCES

Required GDPF resources in terms of personnel, computer time and actual time to produce a one day solution are given in "l"able **5.** Members of the operational orbit determination team work on a five day/week schedule. Weekend backlogs are worked off during this schedule. Totals given in Table 5. are for one team member per workstation, For continued operation the GDPF will require a total of three members. The breakdown of tasks for the GDPF team is shown in 'l'able 6. With the automation developed thus far, a single. person could easily handle the nominal production. The remainder of the team consists of backups, a lead, and sustaining hardware maintenance personnel.

CONCLUSIONS

operational orbit determination has been demonstrated for TOPEX/Poseidon using the GPS constellation (-20 satellites), the TOPEX/Poseidon demonstration receiver, six ground station receivers, the GPS Data Handling Facility and the GPS Data Processing Facilit y. Comparisons between the MIRAGE orbit solutions and other precision orbit solutions based on LASER, DORIS, and GPS yield sub-decimeter radial results. Both the GPS dynamic and reduced dynamic results from MIRAGE appear to exceed the original performance requirements (-one meter radial position) and in fact give results comparable to other geodetic quality software.

Table 5. - GDPF Processing Performance

Processing Phase	CPU Time (hr)	Actual Time (hr)
Data Pre-Processing*:		
Collection	0.1	0.1
TOPEX/Poseidon Editing	1.3	1.4
Ground Station Editing	0.4	0.5
Editing	0.1	0.1
Reformatting	0.1	0.1
TOTAL:	**2.0**	**2.2**
Orbit Estimation (per iteration):		
Initialization	0.1	0.2
Trajectory Propagation	0.3	0.3
Observation Residual Computation	0.5	0.5
Parameter Estimation	0.1	0.1
Stochastic Parameter Smoothing	0.1	0.1
3 Iteration TOTAL:	**3.3**	**3.6**
Archive	0.1	0.2
TOTAL	**5.4**	**6.0**

*Automated processing performed prior to start of work day.

Table 6. - GDPF Personnel Requirements

Lead*:

Data Conditioning:

Orbit Determination:

Hardware Maintenance:

* Lead will also assist and backup data conditioning and orbit determination functions

ACKNOWLEDGEMENTS

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